Thinking the contentfor physics education research and practice

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Abstract

Content analysis, it is unanimously agreed, is a fundamental component of physics education research. In this address I will discuss, on the basis of several examples, how various research standpoints resulted in different ways of reexamining - "reconstructing", or "spotlighting" - the content for teaching: student-led, teacher-led, responsive, proactive. In so doing, I will reconsider, in particular, the merits of "simplification". I will plead for a way of spotlighting the content for teaching that leaves room for the search for consistency and conceptual links, making these explicit, while respecting a constraint of accessibility. The examples of colour phenomena and the transfer of light will serve to illustrate this objective. The final discussion will bear on how students' intellectual satisfaction might thus be increased, and constitute a powerful incitement for them to engage with physics.

Introduction

Everyoneagreesthat content analysis is a constitutive component of physics education research (PER). Since this research domain wasfirststudied, in the seventies, a thorough examination of the contenthas been considered the first essential step of any investigation, in contrast with more general approaches to “science education”. However, some collective works or meetings were launched in the nineties (Fensham *et al.* 1994, Bernardini *et al.* 1995) with the declared goal ofstressing the crucial importance of reflecting uponthe contentthatistobetaught, andconveyed animplicit criticism of contemporary research, seen as too generalist. Since then, several research programs, such as “Didactical structures” (Lijnse 1995, 2002), analyses of “Learning demand” (Leach& Scott 2002, 2003),or discussionson“Learning progressions” (Duschl 2011), haveconverged in underlining that content analysis is central and, toagreatextent, problematic, in physics education research. The influential movement of “Educational reconstruction” (Kattman*et al.*1995, Kattman & Duit 1998) hasstrongly reinforced the idea that research in education for a scientific domain has to involve, as a basis, a “dialogue” between content analysis and aknowledge of students’ common ideas. When it comes to discussing the appropriate conditions for teacher training, the strand of “Pedagogical Content Knowledge”makes ample room forthe idea that the content should not be analyzedand discussed independentlyfromthe other components of the teachers’ competence.

An idea serving as a (nearly) common denominator, in this respect, is that content should be known by researchers in PER, analyzed, elementarized, simplified, andreconstructed for teaching. In most of the diagrams proposed to schematize appropriate interactions in this process, a dialogue is suggested (double arrows) between “subject matter analysis” and “students’ pre-scientific conceptions” – as in the case of “Educational reconstruction” (ibid.) - or equivalent wording is used.Although they are crucial factors, the rolesof the teachers’ level of acceptance of a reconstructed content and oftheir transforming trends (Pinto 2005) will not be broached in this paper. However, it seems clear – *a minima* - that, in the process of content reconstruction, formal accessibility is a constraint to be respected, in view not only of students but also of the teachers.

This paper addresses the following question, here limited to the domain of physics: to what extent and how was the content actually revisited in the frame of more or less recent investigations in physics education research? Far from beinga complete account of all that has been produced in recent years, the objective of this paperis rather to sketch possible modalities forbasinga content analysis onresearch in physics education. After an attempt to characterize a few of these modalities, an example of a"content driven interactive pathway" - about theabsorption of light - will be presented to illustrate how a particular content can be revisited and "spotlighted" for teaching. With this last example, the process exemplified will borrow from several of the types previously characterized. All of these examples are intended to nourish a final discussion about the stakes of revisiting the contentfor teaching, keeping in mind the general injunction to simplify while not losing sight of other essential aspects.

In this discussion, a pivotal idea will be that physics is a widely coherent set of theories, aiming at providing a unified and predictive description of the material world.

Responding to students' ideas: a mirroring effect (model 1a)

A first observation is that, in many of the suggestions for teaching made in the wake of research investigations, there was no particular stress or injunction to reconsider the content in a significant way. There was great progress, in such works, because they localized students' misunderstandings, ascribed mainly to "naïve ideas", "previous ideas", "alternative conceptions", "pre-scientific conceptions", etc., and ensured that these were given full attention, in particular via targeted questions. Such were the perspectivesinPredict/Observe/Explain (White & Gunstone 1992) or Elicit, Confront, Resolve (Mc Dermott 1996). More recently, many strategies based on "cognitive conflicts" and/or "active learning" did not have a content mapping thatwasclearly distinct from the usual one, although some epistemic aspects were given a new emphasis (see the "epistemic axis" in Meheut & Psillos 2004). Thus, the status of models Vs the"material world" was one of the targets thatseveral sequences about particle models hadincommon(Méheut & Chomat 1990, Vollebreght 1998), or problem-posing approaches (Lijnse 2002, Gil-Perez 2003) were intended notably to transform the teaching of some topics. But the conceptual structure of the content was not always substantially transformed, far from it.

In order to explain such stability, when observed, a model of the (non)transformation of the content analysis might be proposed (model 1a). It is intended to describe a stabilizing process, outlined in Figure 1. In this model, students' common ideas are central, asis widely recommended. Once identified, they generate some responses from the designers of research-based teaching learning sequences. But, before that step, it is worth noting that the "common ideas", to put it briefly, have been most often identified by contrast, and in one-on-one correspondence, with various items of the currently taught content. Let us call these items "references" for the observed common ideas. These references are extracted from the most common mapping of the content. Once the knowledge of common ideas has given birth to some targeted changes for teaching, there is a high probability that the "remedies" will be re-injected in the taught content more or less at the same place as the reference items, and be inserted in the initial global structure. This might explain why the content analyses underlying the design of some research based teaching sequencesmirrorthe most current one.

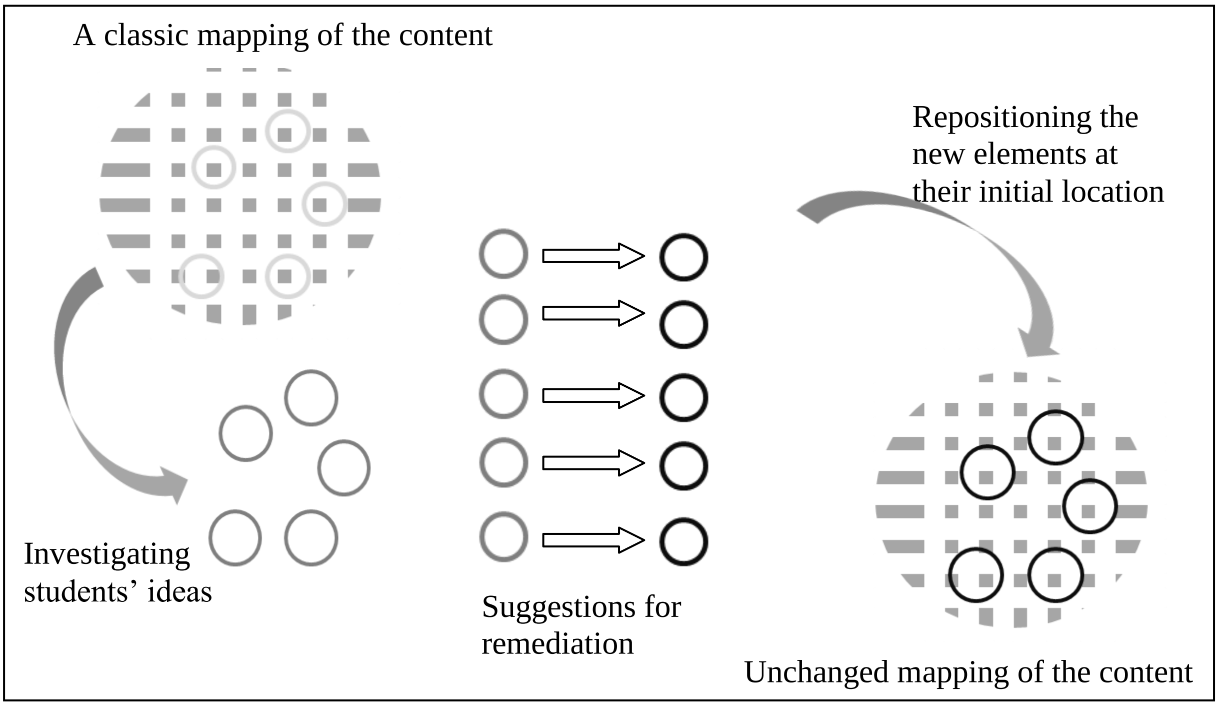


Figure 1. Responding to students' ideas: new taught content closely mirrors initial content. Black circles symbolize changes informed by knowledge of thestudents' ideas (grey circles).

For instance, in the first steps of aresearch investigation about electric circuits, theeveryday meanings of current and thestudents' sequential reasoning were consensually identified as obstacles to a proper understanding of the content. In terms of content analysis, the suggestions for teaching made at that time were to emphasize such and such aspects, in particular via targeted questions or analogies, rather than to restructure the domain.

According to McDermott (1998, see also Shaffer & McDermott 1992), the recommended guiding process towards a comprehension of electric circuits involves a series of experiments from which students "draw inferences" concerning current and resistances. Students are said to "develop operational definitions through which they quantify the concepts of current, potential, potential difference and resistance". Even if, via the finite lifetime of the battery, the idea is stressedthat what is "used up" is energy and not current, the content analysis underlying this project remains very classical. Its essential novelty resides in the instructional strategy, which is already a very important and valuable first step.

By contrast, in some cases, the recommended conceptual goals may be seen as engaging the contentmore deeply. In a review about the *Learningand understanding of key concepts in electricity*, Duit and von Rhöneck (1998) recapitulate the state of affairs in this domain in 1998. Besides therecommended instructional strategies, often based on eliciting students' ideas and more or less continuous views on conceptual change, they report briefly on various aspects of the"Student oriented structure of science content". According to this review, two key concerns were: the differentiation between current flow and energy flow and the differentiation between intensity and tension. These aspects cannot really be presented as new, in terms of content analysis, as compared to the current courses in this domain. They were just presented as crucial aspects deserving emphasis. The third "key concern" mentioned in this review, i.e. a systemic view and the simultaneity of changes in a circuit, already pointed out by Härtel (1985, see also Closset 1983, Shipstone 1984), deserves a more nuanced comment, as it may be argued that this was really a novel idea, due to its transferrable aspect

(Viennot 2001). This “key concern” announces the more radical type of change described below.

In passing, this first example –electric circuits – shows that the categorization put forward in this paper cannot be clear cut. Rather, it defines some extreme cases of how conceptual goals are redefined for teaching.

Responding to students’ ideas: a modified content

A few examples – particularly about elementary optical imaging and friction - introduce the following idea: some “responsive” aspects of teaching may, *de facto*, change the conceptual target itself. What might be seen merely as a “method,” intended to remedy students’ difficulties, in fact goes into the content deeply.

Optical imaging

Among the best known “common ideas” considered as obstacles in the teaching-learning of physics, are those accounted for with the model of “the travelling image” syndrome. The word “conception” seems appropriate here, to designate commonly observed question-and-answerpairswhich are consistent with a view of optical imaging as the reception of an image (or something) travelling as a whole. In the eighties and nineties, several investigations bore on situations like “a mask on a lens” and the frequent studentprediction that it would make “a hole in the image”. Moreover, some criticismswere very soon formulated (Beaty 1987) concerning the possible role of the diagram currently used to find the position and size of an image formed by a thin lens (Figure 2).

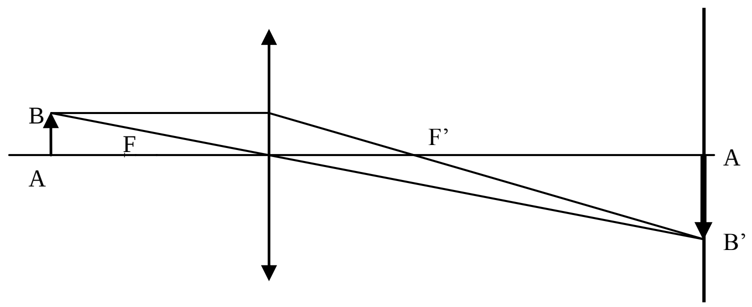


Figure 2. A classic diagram concerning optical imagery with a thin convex lens

The horizontal structure of this diagram and the restricted number of rays represented (rails for the images?) were seen as possible reinforcements for inappropriate views.

In this context, a different type of diagram was proposed and its impact was evaluated (Viennot & Kaminski 2006, see Figure 3).

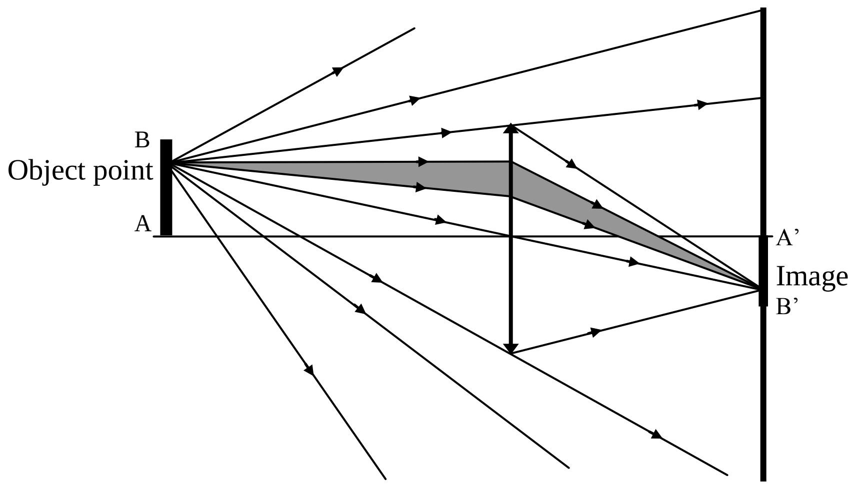


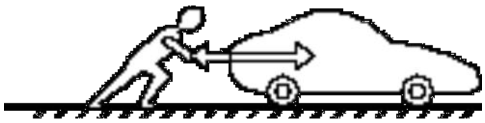
Figure 3. A diagram proposed to underline the process of image formation

A student's comment was particularly striking: "what was really new and decisive for me was the un-deviated rays that pass by the lens".

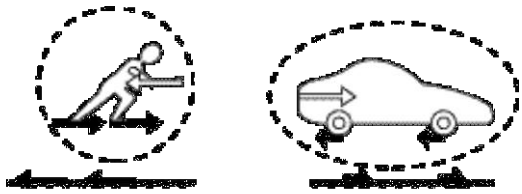
This statement retains attention because, at first sight, these rays around the lens seem totally useless and therefore irrelevant to this topic. However, they attest to a crucial fact: the lensinteractswith only a part of the incoming flux, and transforms it geometrically. This diagram with "useless rays" points to the very nature of the process of imaging. Once this is understood, a part of the lens can still be seen as a lens, which intercepts a part of a part of the incoming energy. Ultimately, what is at stake is a first access to the status of an extensive quantity –energy- vis-à-vis this topic of imaging. *De facto*, the targeted content has changed.

Solid friction

Nearly as well-known as the preceding example, students' difficulties with solid friction are often interlaced with their common views about the third law. As a result, a diagram like theone in Figure 4a is often observedfor a driver pushing his car toward a garage. When presented with a possible conceptual aid, i.e., fragmented diagrams(Figure 4b, Viennot 2003, 2004a), some students in thefirst year at university willingly acknowledged the consistency between this model and Newton's laws: "Yes, this forward force, we need it". But this first response from theteacherdidnot suffice, and a student said: "But the ground is motionless, it cannot push". When the teacher responded once more, this time by pushing on a nearby wall, she was contradicted again: "But the ground is horizontal, it cannot push". Then a model was proposed for the respective profiles of the ground and of the sole: saw-teeth. Figure 4c shows how evocative this model is, and a student's comment attests to its explicative power: "it's like pushing on little walls".

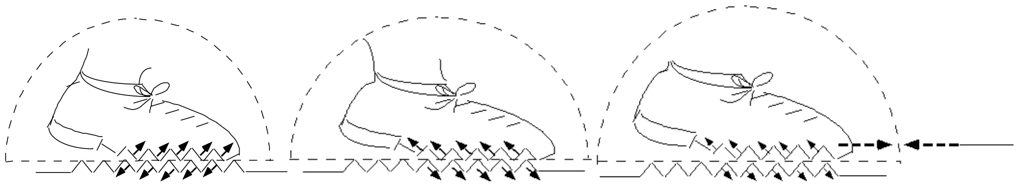


a A common diagram for a walker pushing his car



b A fragmented diagram (horizontal forces) for this situation

c A saw-tooth model: fragmented diagrams for …



a walker who accelerates   a walker who slows down   a shoe pulled with a string

Figure 4. Walking and pushing: a common diagram (a) and two suggestions for teaching (b, c: Viennot 2003, 2004a).

The point of interest here is that, through successive responses to students' difficulties and objections, a new aspect of content was injected in the discussion: a first approach to a mesoscopic model, that is, to a scale of analysis now very much in use in physics research (Duran 1999, Krim 2002).A similar approach was used soon afterwardswith the topic of fluid statics (Besson & Viennot 2004).

Some other cases

Table 1displays some other examples of investigations that have, foralongtime now, beentaking students' views into account in this way. A responsive process hasled their authors to rethink the subject matter, thus presenting their students with aspects of the content not commonly highlighted. Of particular interest is the rationale stated by Chabay and Sherwood (2006), concerning their project in electricity and magnetism(Chabay and Sherwood 2002): ittakes the common trend toward linear causal reasoning into account. The idea (see also Psillos 1995, Barbas & Psillos 1997) was to do justice to this common approach by explicitly dealing with transients in the realm of electric circuits, thus avoiding abruptly confrontingthestudents with quasi stationary regimes. As compared to thechanges previously mentioned, this one is much more radical. Indeed, the teaching of electro-magnetic phenomena was usually divided into electrostatics, magneto-statics, electric circuits in quasi-stationary regimes (including variable currents), and waves. It was really a novel choice to focus on the propagative transitory phase ($\cong 10^{-8}$s) between a static situation – a battery and its ends – and what occurs between the time a circuit is closed and the quasi-stationary regime is established. This choice makesitpossibleto reconcilethestudents' tendency to adopt a linear causal reasoning and the counter intuitive systemic view of a circuit.

The following quote (Chabay & Sherwood 2006) expressesthe authors' perspectivevery clearly:

> Some research and development in physics education has focused on remedying particular problems with the traditional sequence by giving students additional focused practice on selected concepts. However, without addressing the overarching issues of structure and coherence, it is difficult to do more than improve student performance on isolated tasks. We have chosen instead to reexamine the intellectual structure of the E&M curriculum to identifywhich concepts are centrally important, how these concepts are related, and how they can be introduced to students at the introductory level in a coherent, comprehensible sequence.

Table 1. A few examples of a new content spotlighting, in response to students' common ideas.

Students' common perspective	Common comments	New spotlighting of the content
The « travelling image » syndrome	We can see an image without a lens, erect this time. A mask on the lens, then a hole in the image.	A new diagram with"useless" rays, the imaging process, role of energy (Viennot &Kaminski 2006)
Friction: "the ground cannot push".	The ground is motionless, it is horizontal, it cannot push.	The mesoscopic approach: a saw-tooth model (Viennot 2003)
Pressure in fluids: a manifestation of weight	The fish in the sea feels greater pressure than in the cave (same depth)	The mesoscopic approach: The sponge balls model (Besson & Viennot 2004)
Third law : *de facto* denied	The table cannot exert a force	The deformable table (Brown 1994, Clement *et al.* 1989)
Electric circuits : sequential reasoning	The second bulb (*in a series circuit*) lights less.	From electrostatics to quasi-stationary currents, via the study ofpropagative transients (Barbas & Psillos 1997, Chabay & Sherwood 2002)
Vision without light in the eye	I can see the ray.	Discuss: dazzling, more or less light (de Hosson & Kaminski 2007)
Archimedes' principle not seen as an interaction	It has nothing to do with pressure	Discuss: making holes in water (Ogborn 2012)

Responding to students' ideas: a new spotlighting of the content (model 1b)

The precedingexampleslead to, or echo, a notion previously suggested to characterize what it means to think about the content for teaching: the *spotlighting* of a content (Viennot 2003, 2004a, b).

In these examples, what has been changed in the research process is a way of seeing the content: angle of vision, field, zoom, contrast. It is not mere simplification. If an "elementarising" process is at stake, this relies by no means on a straightforward mapping of the content. What is transformed is not a series of items, it's a particular view of the content. In terms of selection, it is also that of a global aspect, not only a matter of local changes.

The label "spotlighting" was chosen to suggest that no new content, *stricto sensu*, is invented. As with a photographer with a given landscape, the reflexive decision on what to stress in the taught content leads the planners to emphasize, unify, differentiate, contrast, various elements according to particular goals. The invention is there, only there, even if « Making explicit what was implicit before and stressing it is nearly like creating a new content » (Viennot 1995, 73).

Figure 5 suggests in a metaphoric way what makes the construction of a new spotlighting really different from a series of fragmentary responses (i.e. model 1a): A more global reorganization of the content is aimed at. Figure 6 sums up how the dialogue between content analysis and the investigation of students' ideas may crucially involve an effort to stress the consistency of physics and highlight its crucially important concepts.

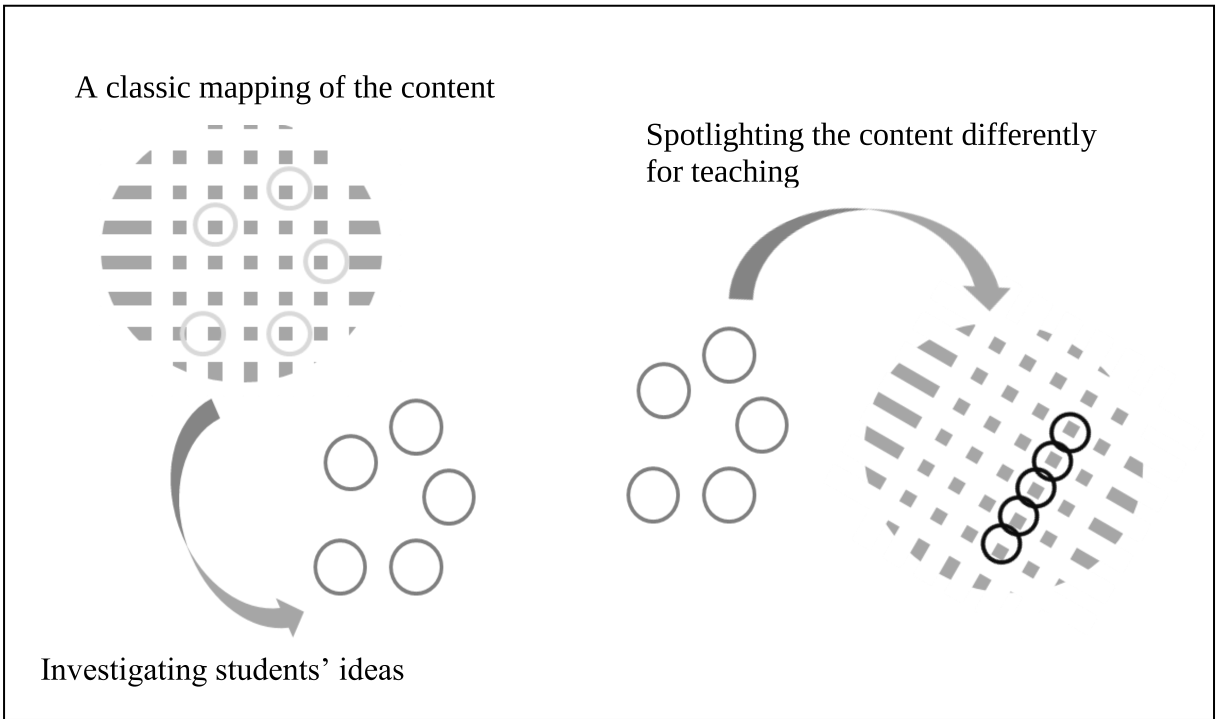


Figure 5. Taking into account students' ideas by spotlighting the content differently for teaching. Black circles symbolize changes informed by the knowledge of students' ideas (grey circles).Strictly speaking, a three dimensional diagram would be needed to account graphically for the "alignment" of previously unrelated items.

It may happen that the new structuring at least partly "legitimates" some common ways of thinking, producing a "work with it" style described, for instance, by Duschl *et al.*(2011, see also Clement*et al.* 1989). This is typically the case with the idea of analyzing propagative transients in electric circuits, or in the teaching sequence about friction cited above.

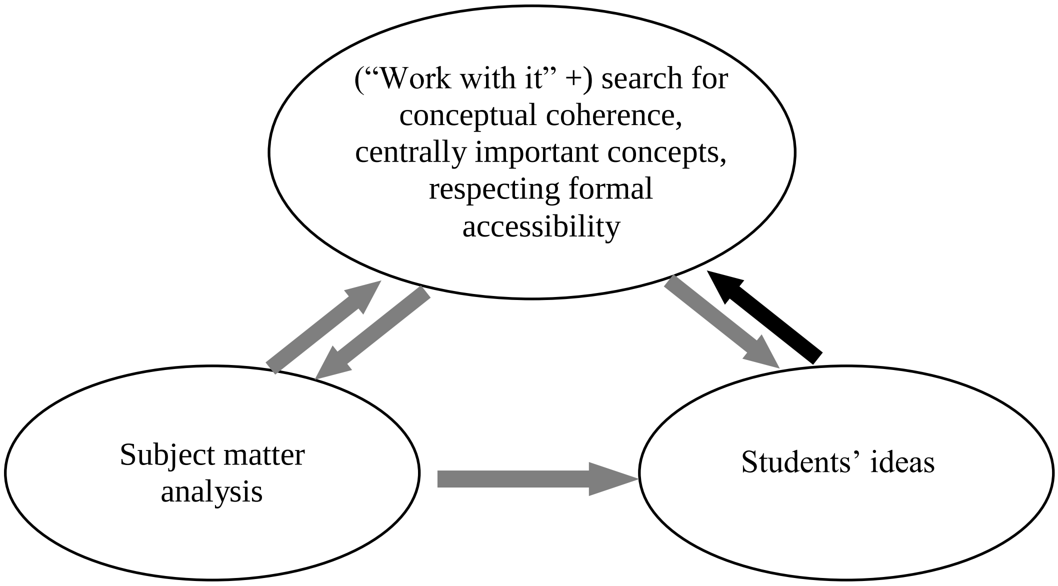


Figure 6. Taking into account students’ ideas, possibly in the “work with it” modality (Duschl 2011), by differently spotlighting the content for teaching: a process rooted in the search for conceptual coherence (model 1b). Black arrow: the decisive aspect that triggered a restructuring process.

Teaching rituals and responsive spotlighting of the content (model 2)

These two ways of revisiting a content analysis in the light of students’ common ideas (models 1a and 1b) do not cover what was done in this respect in previous research. Some revisitings of content were triggered by the pinpointing of teaching rituals (Viennot 2006). Two examples follow.

From global to local: the hot air balloon

Particularly informativeis the common statement in exercises about a hot air balloon. The target is to find the condition in which the internal temperature enables the balloon to stay in the air, andthe following hypothesis is quasi-universally enunciated: Internal pressure is equal to “atmospheric pressure,” which means an isobaric situation. The explicit or implicit reason for this decision is that the hot air balloon is open at its lower aperture. This hypothesis permits an easy calculation of the required condition, via Archimedes’ theorem and a perfect gas relationship. But, although the exercise can be solved easily thanks to this apparently reasonable hypothesis, the situation modeled in this way would be catastrophic for the balloon: a crash is to bepredicted. One argument to support this prediction is that, with the same pressure on both sides of the envelope at every point, no resulting force would ensure the balloon’s sustentation. One may also observe that an isotropic field of pressure is not compatible with a thrust in any privileged direction, i.e., upwards, here.

A responsive presentation of the related content, summed up in Figure 7, consists in emphasizing the core of fluid statics theory: it’s all a matter of gradients. No pressure gradient means no up-thrust. The fact that the balloon stays in the air is intrinsically linked to the change in pressure with altitude. From the aperture to the top of the balloon, internal pressure diminishes more slowly than external pressure, due to different densities of the air inside and outside the envelope. This argument, which admits that the two pressures are equal at the bottom of the balloon, accounts for the fact that the envelope is inflated and stays in the air.

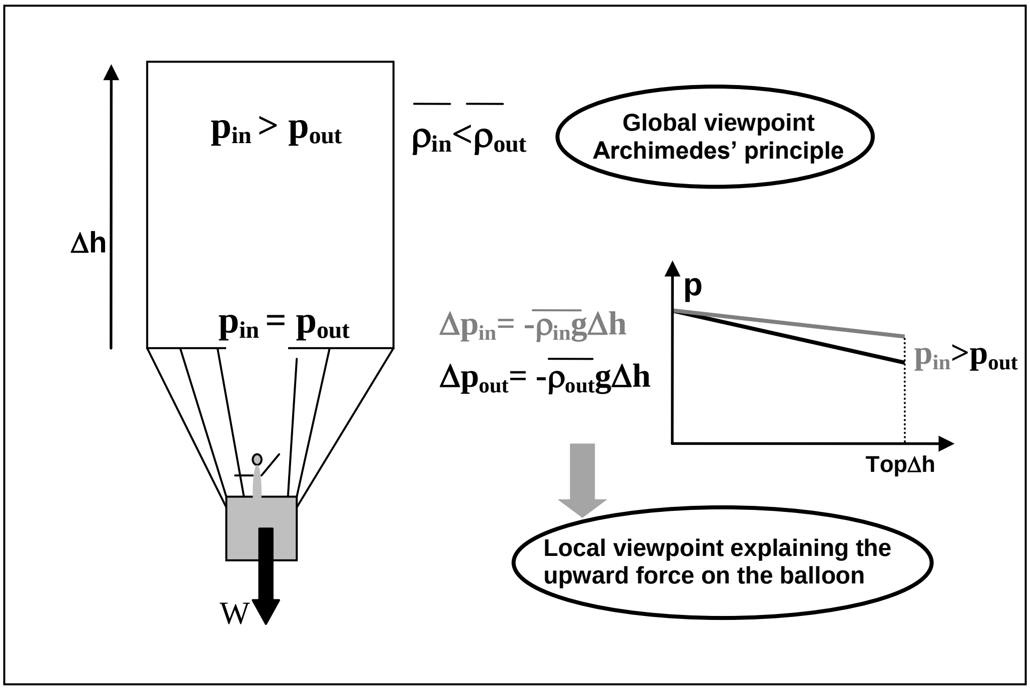


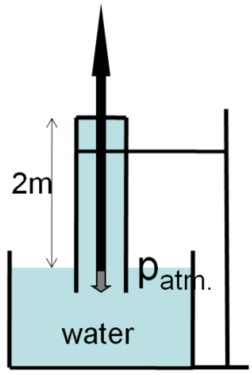
Figure 7. Some elements needed to understand how a hot air balloon stays in the air.W:weight of the system (basket+load+balloon). The unlikely cylindrical shape is intended to facilitate the understanding of how a resulting upward force is linked to a difference between internal and external pressure (Viennot 2006).

To sum up this responsive process, the spotlighting of the content changed from a global approach –linked to Archimedes' theorem- to a local analysis of the mechanical forces exerted on the envelope. In this case, it may be reasonably hypothesized that the observed global approach, leading to a correct answer, is to be attributed more to the teachers'choice than to the students' pre-scientific views.

From the local to thesystemic: examples in fluid statics

Some teaching rituals may favor a local analysis and lead to suggestions for content spotlighting centered on systemic approaches. Thus, again in fluid statics, several situations have commonly given rise to local interpretations, like those suggesting that the column of water in an inverted glass (Figure 8a) exerted its weight on the cardboard, itself subject to a force due to atmospheric pressure (Viennot *et al.* 2009, Viennot 2010). Marie Curie (Chavannes 1907/2003) gave a similar comment for the column of water in a test tube inverted over a tank of water (Figure 8b). In all similar cases, the explanation is inconsistent with Newton's second law, and it seems appropriate to counterbalance such trends by spotlighting the systemic status of the situation: then the two "ends" of the system, broadly speaking, for instance the top and the bottom of a column of water, will fruitfully be taken into account. Acting on the upper recipient of a love-meter with cold water shows that both "ends" of the system matter.More generally, other examples illustrating that differencesmake the world go round (Boohan& Ogborn 1997) refer to the same concern (Viennot 2014).

Two inappropriate explanationsin fluid statics



What is lifting this column of water up by 2m? It's atmospheric pressure that is pushing on the water in the tank. **In the tube**, there is no air, and **no pressure is exerted on the wate**r.

M. Curie/I.Chavannes 1907/2003
a

Cardboard will support water. If turned around, the **cardboard feels** atmospheric pressure from below, but **only hydrostatic pressure of**(…)**1/100 of atmospheric pressure** from above.

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Figure 8. Two analogous examples of ritual and inappropriate analyses for physical systems: sentences in black are erroneous: They are compatible with the idea that an object always exerts its weight on its support. The diagrams are drawn by the author of this paper (not to scale) to point out that the forces mentioned in the quotes are unbalanced.

It is worth noting that, concerning the inverted glass, the responsive process may be said to start with the analysis of rituals, but at the same time these rituals are in resonance with some of the students' trends of reasoning, namelya local reasoning and thinking that an object always exerts its weight on its support. The label "echo-explanation" has been proposed to designate such cases (Viennot 2010).

In this case as with the previous one (the hot-air balloon), it is particularly manifest that the responsive process centers, on the part of the researcher formulating this proposal, on the desire to highlight conceptual coherence, links and key ideas in physics - here the need to consider *both ends* of the systems (Viennot 2010, 2014).

A specific model is proposed (model 2, Figure 9) for this process of content spotlighting prompted by a teaching ritual, whether or not it is also seen as a possible response to students' common ideas.

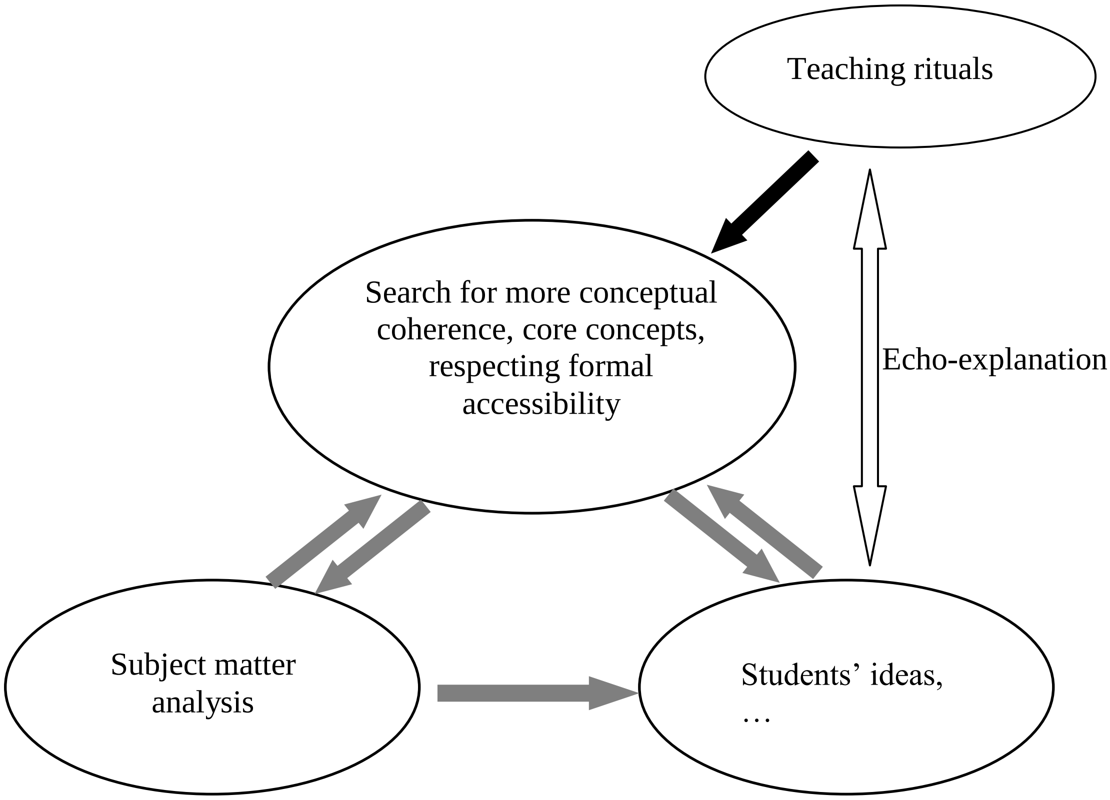


Figure 9. A model for a process of content spotlighting which is triggered by the analysis of a teaching ritual (model 2). Black arrow: the decisive aspect thattriggered a restructuring process.

In fact, this desire has long inspired many teaching projects.

Proactive emphasis on conceptual coherence, links, strong ideas in physics (model 3)

It is not within the scope of this paper to recapitulate and analyze the multiple attempts made in the recent past to re-think physics for teaching, in the perspective of highlighting conceptual coherence and key ideas in physics, while respecting a constraint of accessibility. But it is worth noting that some famous instances of this effort preceded the start of what we now call Physics Education Research: *The Feynman Lectures on Physics* (Feynman *et al.* 1964-1966), the*Physical Science Study Committee*project(1960), the *Harvard Physics Project* (Holton 1969), the*Nuffield projects* (Fuller & Malvern 2010), for instance, were clearly inspired by this objective. Contemporary with the first research investigations in PER, the innovative reflections on the theme of *Change and chance* (Black & Ogborn, 1970-1979), or on energy (Boohan & Ogborn 1997) for instance, were of the same type. These high quality projects may be seen as typical of a proactive attitude (see also Michelini *et al.* 2000), which was not rooted in a precise knowledge of what students commonly think, even if some general considerations about the targeted audience were mentioned in their rationale. The reasons for their relative failure (French1986)might include this lack of precise knowledge about students' difficulties, to say nothing of the teachers'. We simply mention these projects here in order to characterize acase (model 3, Figure10) among attempts at re-thinking the content.This perspective is still present, to a greater or lesser extent, in more complex landscapes - the above "models"- of subject matter reconstructions.

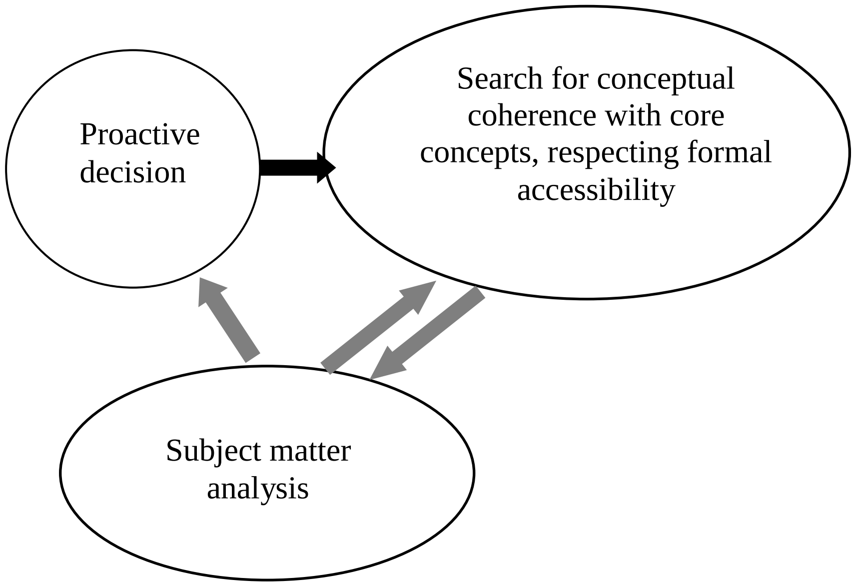


Figure 10. Proactive reconstruction of the content, not explicitly inspired by a detailed analysis of students' ideas and difficulties (model 3). Black arrow: the decisive aspect thattriggered a restructuring process.

A "multi-source" spotlighting of content

After this attempt at characterizing different starting points, reasons and ways to reconsider the content to be taught, it's time we remarked that nothing prevents us from blendingthese types of processes for a new spotlighting of a given topic. The following example is rooted in the combined consideration of some rituals and students' common ideas, as well as of conceptual coherence, links and strong ideas. The next section is devoted to a brief description of this twofold investigation (Viennot & de Hosson 2012, 2014), with a focus on the underlying content analysis. In this particular example, the conceptual structure that was privileged is inserted in the frame of a particular teaching format: concept-driven interactive pathways (CDIP), keeping in mind that the "multi-source" character of a renewed content analysis could be observed with other teaching formats as well.

A multi-source spotlighting of the absorption of light: two CDIPs

A teaching format: Concept-driven interactive pathways

The expression "Concept-driven interactive pathway" (CDIP) designates a type of teaching sequence with the following characteristics (Viennot & de Hosson 2014):

-It is designed with the goal of facilitating students' access to the understanding of a given conceptual content.

-It is interactive, implying teacher-student or teacher-group interaction. It may comprise phases like: exploring and discussing students' ideas, asking for argued predictions or diagrams and discussing these with students, letting students construct and analyse experimental results, injecting new ideas in a transmissive style, having students' criticize documents, etc. This adjective, "interactive", refers to this statement: "Teaching is acting on other minds who react in response" (Ogborn *et al.* 1996, 141).

-It organizes a pathway, that is, a step-by-step process designed to help students progress toward the desired target. Although the structure of the pathway is mainly concept-driven, the development of transversal abilities – such as the critical faculty - isalso favoured.

With such a format, the particular spotlighting of the content is of crucial importance, as illustrated below.

The absorption of light: spotlighted ideas

Two CDIPs on the absorption of light, each intended for an interaction of about one hour, have been designed and implemented (Viennot & de Hosson 2012a,b;Viennot 2013, Viennot & de Hosson 2014). They are briefly described hereafter as well as the main aspects of the students' reactions, with the view of commenting the content analysis on which these CDIPsrely. Depending on the targeted audience and school constraints, the first one may constitute a preparatory step for the second one, or each may be implemented alone. Here, a brief description of our investigation with the first pathway (*CDIP1*)introduces the arguments at the basis of the construction of the second one (*CDIP2).*

Globally these two pathways are intended to spotlight the following conceptual targets:

-The absorption of light by pigments or filters is not an all-or-nothing process.

-It is a multiplicative process, involving multiplication by numbers smaller than 1.

-It is selective, that is, it depends on the wavelength.

These investigations were conducted on the basis of interviews with prospective teachers at university, the first one (CDIP1) with 8 students in the third year, the second one (CDIP2) with 6 students in the fourth year.

The students were put throughthe following steps.

Light and pigments (CDIP1)

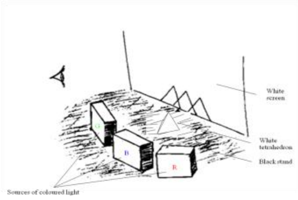
After a brief reminder, the students had at their disposal a sheet (see Appendix) listingthe classical rules concerning the absorption of light by pigments or filters, for instance: a red pigment absorbs the green and blue part of the spectrum of white light (symbolized in three thirds of spectrum). This reminder phase– *P/A* in Table 2 - involved situations of coloured shadows defined by the presence or absence of light on a screen, and binary rules – a pigment absorbs, or does not, such and such apart of the spectrum of white light.

Then, thestudents were asked forjustified predictionson the following question: would they be able to see the impact of a red laser beam on the various parts of a sheet of paper with white, black and colored (red, blue, green, yellow, magenta, cyan) zones; if yes, what would the aspect of the impact be?

With an all-or-nothing understanding of the rules just recalled, the answer would be that the impact would be undetectable with the "red-absorbing" pigments (black, blue, green, cyan), contrary to the others, which would diffusively reflect the incident red light.

Once the experimenthad been performed, it appeared (phase *M/L*) that these two groups of pigments absorbed *more or less* red light, so that the impacts could be localized by *less or more* luminous red spots. Concerning the "red-absorbing" pigments, the target of the interaction was the idea that a few percent of the incident light was enough to detect the impact, because this light was intense. As one student commented, “a few percent of a lot of light, that amounts to something!”The next phase of this pathway was devoted tomatching these “few percent” with the tail of the reflection curves of the concerned pigments. Finally the students were consulted about their intellectual satisfaction and feelings at the end of this interaction.Table 2outlines the structure of this CDIP.

Table 2. Main steps in *CDIP 1*

Phase	**Our conceptual targets and questions**	**Material setting**	**Main aspects of the discussion (planned and/or expected)**
P/A	Students are reminded of the classical rules First observation of their reactions	Coloured shadows 	The students appropriate the classical rules, predictions are made on this basis, observation, discussion, recapitulation. Table of rules left to students
M/L1	Intense coloured light on pigments: Do studentstransfer the classical rules or not if so, how?	A red laser pointer A sheet of black paper with 6 coloured areas: red, blue, green, yellow, magenta, cyan	Predictions with arguments: Impact visible or not, if so, description of the impact, with arguments
M/L2	Performing the experiment: how do they react ? …do they -use M/L approach?		Strong destabilisation expected
M/L3	-understand the multiplicative aspect of absorption? -explain the difference between experiments used in the P/A phase and M/L phase?	Reflectivity curves of pigments	Considerable input from the interviewer to help students understand the meaning of the curves
M/L4	Global evaluation of the design		Feelings expressed

CDIP1: Main results concerning the students’ ideas and reactions

In terms of comprehension, the main results can be summed up as follows:

-A strong destabilisation was caused by the experiment.

-The two groups of pigments were unanimously identified.

-The « more or less » idea was unanimously expressed.

-All interviewees realised that strong sources may « invalidate » the « all or nothing » rules.

-Access to the meaning of percentages was difficult.

The metacognitive and affective reactions of the students will be briefly reported further on.

Light and filters (CDIP2)

The results of this first experimentationinspired us to investigate possible ways to help students to understand the multiplicative status of absorption. We chose to use filters, and made the hypothesis that the dependence of absorption on thickness might be an anchoring aspect for the targeted comprehension. Indeed, to understand the role of the successive, equally thick, layers of a filter, one has to understand that if one layer multiplies the incident intensity of light by, say 0,95, the second will let 0,95*0,95 of this initial intensity pass. Given the selectivity of the absorption, the rates of transmission for another wavelength might be, for instance, 0,3 and 0,3*0,3, respectively. This entails a strong distortion of the curve.

After a reminder phase like in *CDIP 1,* the interviewees (6 prospective teachers in the fourth year at university) were asked which mathematical operation came to their mind in this respect. All responded “subtraction.” Then, they were shown a slide with a slit crossed by filtering strips of increasing thicknesses, made of one, two, three, etc., layers of a light yellow plastic sheet (Figure 11).

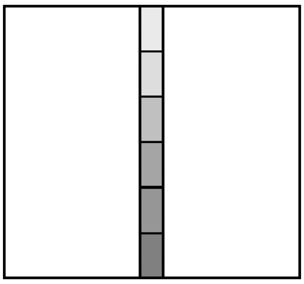


Figure 11. A diapositive with a vertical slit (width about 1mm), covered with one, two, three, …, six horizontal strips made of transparent

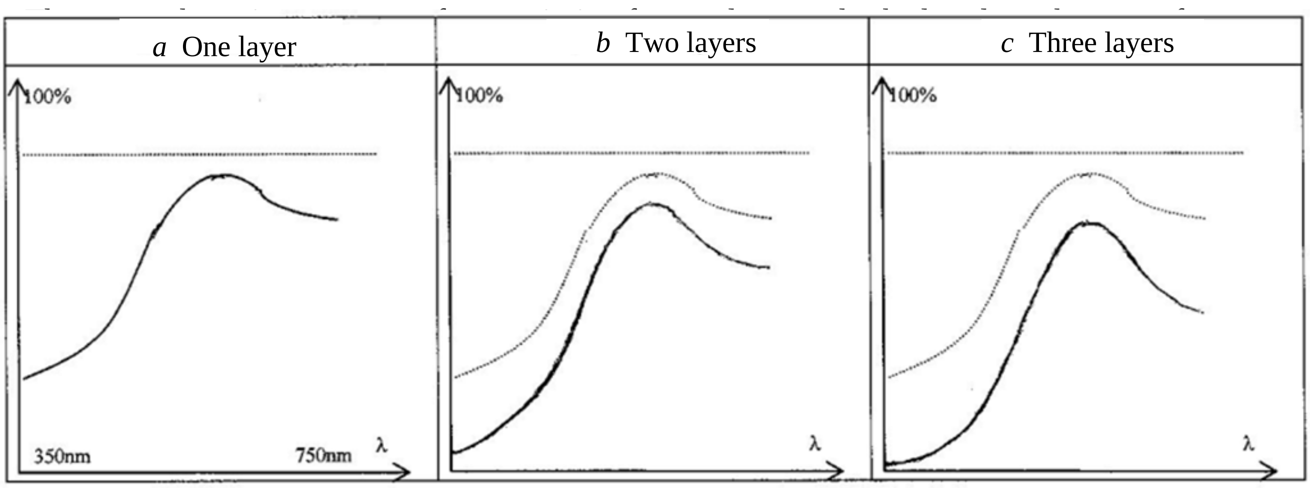


Figure 11. Given the transmission curve for one filtering layer, strips with two or three superimposed layers don’t have a transmission curve of a similar shape.

The drawings and the comments that were collected in this phase show how salient the idea of non-selective subtraction was, in other terms, the downward translation of the transmission curve proposed for one layer (Figure 13).

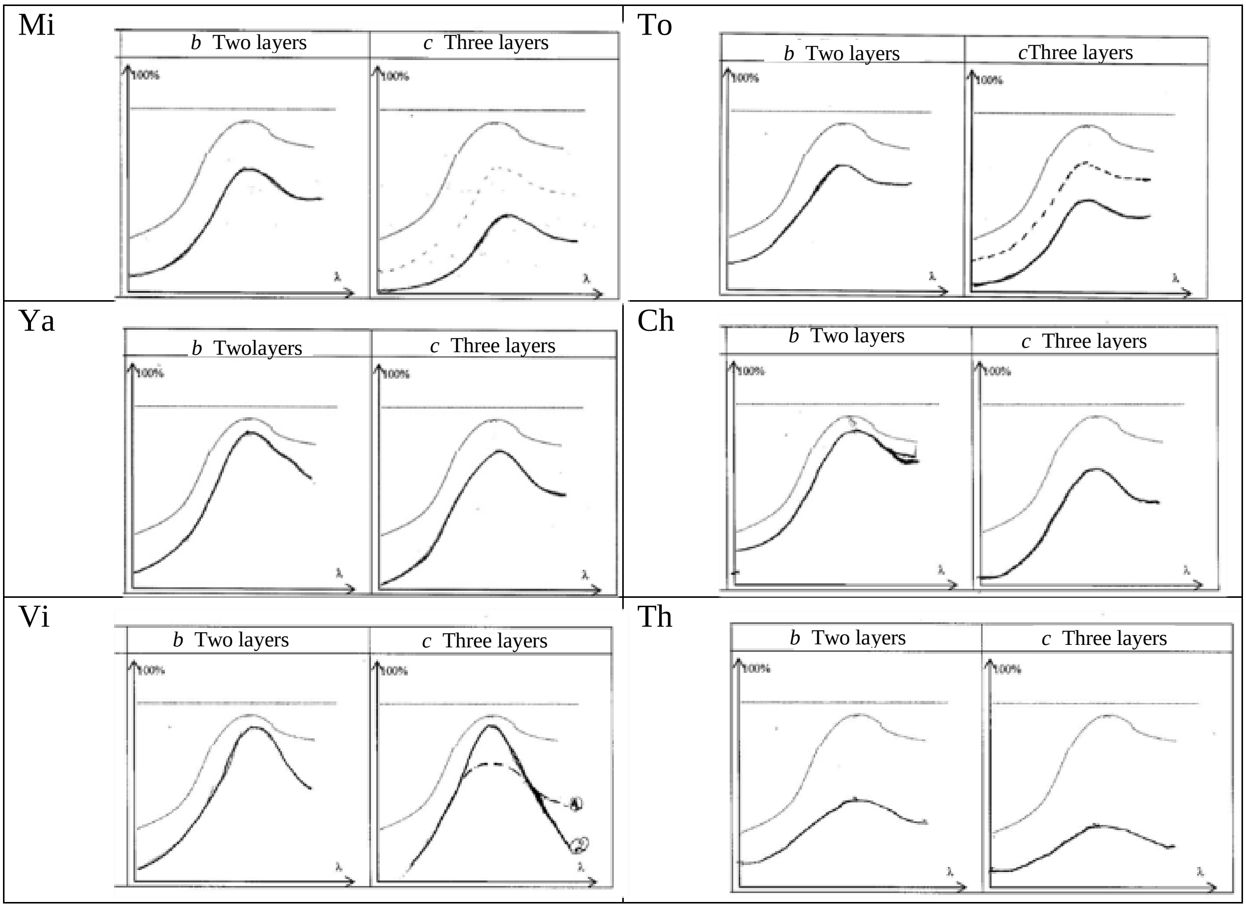


Figure 13. Transmission curves for two and three superimposed filtering layers drawn by students before the corresponding experiment.

The following conceptual target was to use the idea of multiplication to realize and explain the deformation of the transmission curves with thickness.With this object, and also another one made of pink-magenta plastic, some parts of the spectrum (red and green) of the transmitted light seemed nearly unaffected by thickness whereas the blue part disappeared with the three-layer strip (photos of spectra are available in Viennot 2013). The subsequent phases were devoted to the transfer of this new knowledge to other situations, a liquid and a gaseous filter, respectively pumpkin seeds oil and the atmosphere. In these two cases, the change in colour of the transmitted light was explained by the interviewees, after discussion, on the basis of the initially provided transmission curve. Once the possibility of seeing oil or the atmosphere as filters was admitted, it became clear to the students that successive multiplications would come down to selecting the part of the spectrum where the rate of transmission was the highest, i.e. in both cases the “red” part (Figures 14 and 15).

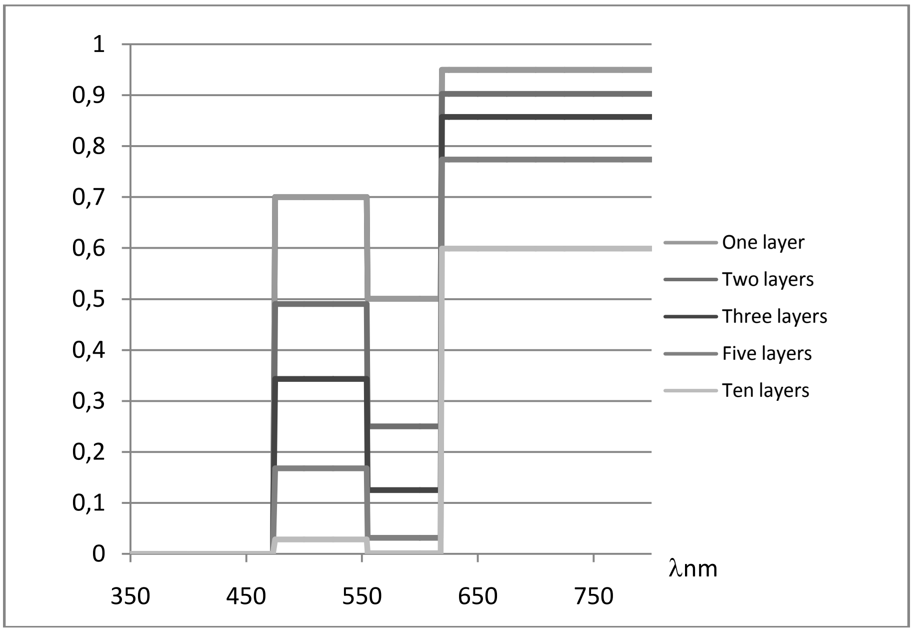


Figure 14. Transmission curve of one, two, three, four, five, ten successive layers of pumpking seeds oil, using a simplified the model of the spectrum for one layer (after Kreft & Kreft's 2007)

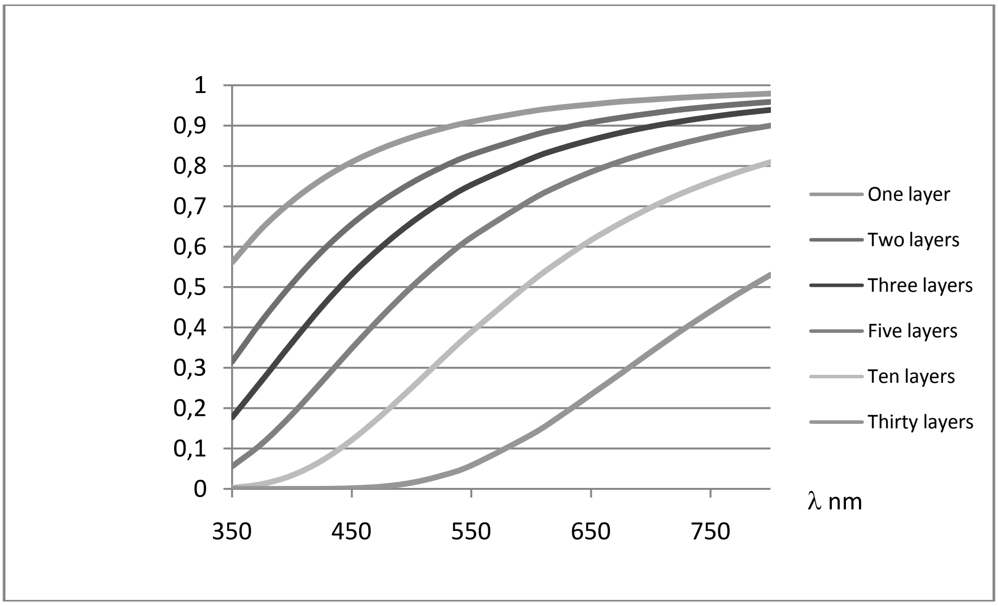
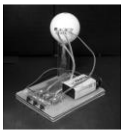
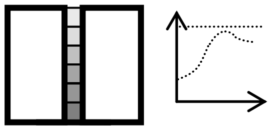
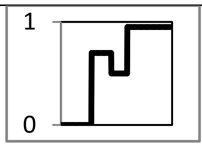
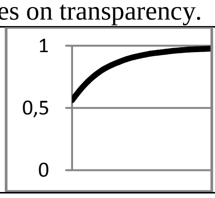


Figure 15. Transmission curve of "one layer" of the atmosphere, i.e. the atmospheric path traveled by light when the Sun is at Zenith (drawing on: Vollmer & Gedzelman 2006, p. 300), then of two, three, four, five, ten, thirty successive layers of atmosphere.

Table 3 outlines the structure of this CDIP.

Table 3. Main steps in *CDIP2*

Phase	Our conceptual targets and questions	Material setting	Main aspects of the interaction (planned and/or expected)
Rem	Students are reminded of the classical rules First observation of their reactions Question: which operation comes to your mind:+,-,*,/?	 A colour mixer	The students appropriate the classical rules; predictions on this basis, observation, discussion, recapitulation. Table of rules left to students Question "which operation …?"
Filt-a	-Draw the curves accounting for the transmission of light through two, then three layers of the same material: Do students just translate the first curve downwards, or do they/how do they change the shape of the curve?	 +Device to project spectra of the light transmitted through each strip	Predictions with arguments
Filt-b	Performing the experiment: Do they change their curves? Formulate a conclusion explicitly using selective multiplication?	Spectra observed	Students asked to reconsider the curves, to account for the disappearance of "the blue" : strongly guided discussion
Oil	Observe colours of the oil, then apply a multiplicative procedure to the curve proposed by the interviewer to account for these colours	 + Sensitivity curves of the cones on transparency.	The interviewer -provides help for calculation. -explains how to use the sensitivity curves of the cones.
Atm	See the situation as a filtering case. Transform the curve provided by the interviewer for "one layer"		The interviewer provides help for -interpretation of the situation as a case of filtering - calculation
Gene	Ask about a function accounting for the changes of intensity observed		Input from the interviewer: (selective) exponential decrease
Mca	Global evaluation of the design		Interviewees express feelings

CDIP2: Main results concerning the students' ideas and reactions

In terms of comprehension, the prevalence and the resistance of the idea of – implicitly uniform - subtraction was very impressive:

> Int *(Interviewer)*: What did you use when constructing your answer, a line of reasoning founded on which type of operation?
>
> Vi : Subtraction, mainly.

Or else,

> To: We add subtractions.

The comments finally attesting to a real comprehension were all the more striking:

> Mi : Given that it is proportional, … *(adding filters)* we will end by selecting the spectral band of greatest transmission factor ...
>
> Th: We've just seen that differences were majored when layers were added.
>
> To: Even after having done this *(a multiplication)* right from the beginning, I wouldn't have interpreted this as a multiplication.

CDIP1 and 2: Main results concerning the students' metacognitive-affective comments

A final observation is worth pinpointing here. Beyond numerous expressions of satisfaction, we note the emergence of some meta-cognitive judgments:

> Th: We've just seen that differences were majored when layers were added. I wouldn't have spontaneously used the word multiplication, I did not reason like that before coming here. (…)Perhaps, I would use the operation with the right data, but if I was asked for an explanation, I wouldnever have used the word multiplication. CDIP2

We find here an echo of several comments collected during a subsequent workshop in a meeting of the European Science Education Research Association (Viennot & Mueller 2013), which was framed on this CDIP:

> -The use of different thicknesses, we usually do it with only one and I had the idea of subtraction. CDIP2
>
> - It made me think about things I knew about intuitively perhaps, but I still think it was as if I did not know about them previously. CDIP2

A critical stance also emergedamong the interviewees at the end of both CDIPs, in this case concerning the binaryrules used in the reminder phases:

> -We have to be careful (with rules). CDIP11
>
> - The (classical) rules (still) have a certain validity. CDIP1
>
> - Given this, should we tell our students, we should use the law of additivity bla bla bla! Is it correct to use it? No, it's true, additivity is OK, it's for subtractivity *(that there is a problem).*CDIP2
>
> - Showing the subtraction, if I may say,of colours, and coming back afterwards to something that comes down to percentages, it'srather, err, I don't know if you would've presented it like that. (…) For a student who is not used to it, it might be very disturbing.CDIP2

CDIP1 and 2: the reasons for a spotlighting

These two concept-driven interactive pathways have several common features in terms of spotlighting. They are designed on the basis of a very fundamental idea, sometimes referred to by the interviewees as a "tough idea". The multiplicative nature of the process of absorption ultimately leads to the exponential dependence of intensity on the crossed thickness (CDIP2). Although this was hardly discussed in the short time we had, the process of absorption is multiplicative because it is statistical. For all of that, the formal complexity,which may seem very little, comes down to that of successive multiplications. It may also seem not to constitute the least "new idea", despite the students' recurrent comments. It is not "new physics", but it is a spotlighting of physics that shows these pathways' distance from the most prevalent teaching rituals, in this case the binary rules of the absorption of light by filters or pigments - still used without any discussion recently (Mota and Lopes dos Santos 2014). Students' ideas are also taken into account, with the goal of extending the range of their line of reasoning when they pass from a view limited to subtraction to a more fruitful multiplicative approach. The decision was also taken to underline the links that physics enables us to establish: a multiplicative process accounts for changes in light which interacts with solids, liquids and gases.In terms of formal complexity, the price to pay is moderate.Simplicity is still favoured via the choice of equally thick layers and a discrete approach to exponential function. At the same time, simplification is kept under control as consistency is not seriously at risk. Figure 16shows a sketch of this proactive and responsive, multi-source process of spotlighting a content for teaching.

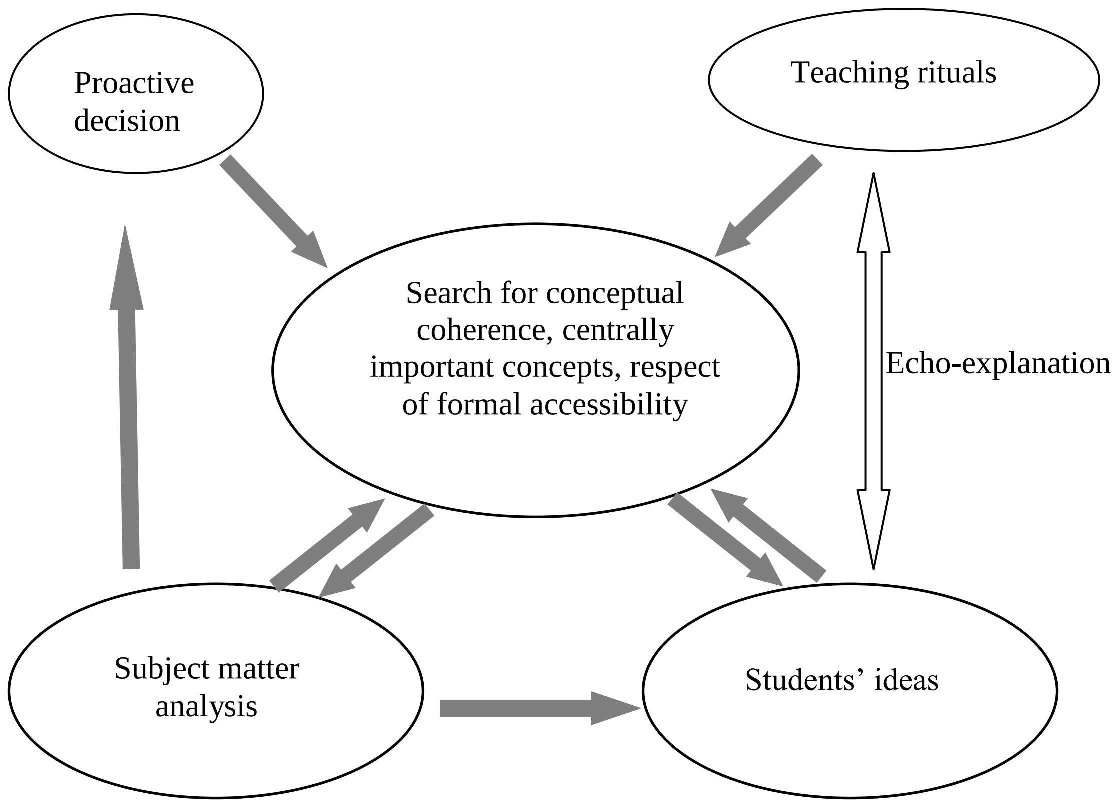


Figure 16. A multi-source process of content spotlighting, as in the case of CDIPs about absorption of light described here.

Recapitulation and concluding remarks

In the light of the preceding analysis and of the various examples analyzed, some ideas seem todeserve consideration. With the first of the models proposed for the reasons for casting a new look at taught subject-matter, it is suggested that taking into account students' ideas is not enough to ensure an actual revision of the content. Rather, it appears that a stabilizing process may intervene, the "new" elements being in fact re-injected in the initial mapping of the content. This is not always the case, far from it, and examples have been given in which a new "spotlighting" of the content was designed in response to some features observed in students' thinking. This said, ascribing a label of "newness" to such and such a suggestion is debatable, and the corresponding categorization cannot be clear cut. Rather, it defines some extreme cases of how conceptual goals are redefined for teaching.

A new spotlighting of a given content may also result from a response to some teaching rituals, with or without a concomitant awareness of students' difficulties. These difficultiesmay or may not be in resonance with the rituals, as the label "echo explanation" suggests. In most (all?) cases of a really new look at the content, a thorough consideration of the coherence, links and key ideas of physics is likely to be at work.

These reflections about new spotlightingdistinguish between what it is to fruitfully re-think the content and the mere ideas of elementarisation and of simplification–if understood as unproblematic. In particular, simplification is not the master word in the previous examples. A smooth and horizontal ground may seem more simple than a saw-toothed profile which, however, proves more favorable to a sound comprehension of solidfriction. To say nothing of the incoherent “simplicity” of an isobaric hot air balloon. In any case, simplification should be kept under control, and negotiated, keeping in mind the imperative of consistency. It is also worth noting that there is room for opening and enlarging a content analysis without ending up with excessive complexity. The last examples -namelythe content driven interactive pathways about the absorption of light just described- illustrate, we think, the merits of a proactive/responsive, expert-leddesign of « new » spotlighting of content (i.e., led by a researcher and/or teacher): a design emphasizing consistency and conceptual links, as well as spurring an active engagement on the part of the students. Finally we might remark that the adjective “new” may seem deceptive, given that there is nothing new, strictly speaking, in the aspects of physics mentioned in this paper, apart from the decision to cast light on them. Here “new” does not mean reinvented physics, it means that attention is given to aspects of physicsthat have been commonly disregarded, or kept implicit.

One may wonder what possible obstacles may block this open reconsideration of content. Among good candidates, we suggest: a lack of distance with respect to rituals, an *exclusive* centering on students’ ideas with a « mirroring effect », *excessive* belief in (and focusing on) the power of new methods,the possible identification of « more rigorous » with « boring », and the common view that what is good for teachers cannot be good for their students. Clearly, more research is needed to give more substance to these assertions.

The preceding reflections also point to twostrands of research ofcrucial importance, concerning fruitful ways to determine the content for research and practice.

One is the connection we can observe in studentsbetween an active search for consistency with conceptual links, on the one hand, and their intellectual satisfaction on the other. Without denying the motivation that can be raised via other entries, it would be highly contestable to deprive our students of teaching situations of the kind that make them conclude: “Thank you, youmade me think”. But this connection between the affective and intellectual aspects is not straightforward, and deserves thorough attention and research.

Secondly, we have pointed out the limits of approaches to teaching that would rely on a separation between comprehending the content and developing certain competences. With the last examples reported here, it was particularly clear that conceptual development and a critical stance were not independent. A certain level of comprehension seems to be needed to trigger a critical attitude, even if the students’ initial knowledge was *a priori* sufficient to achieve this goal (see also Mathé & Viennot 2011, Viennot 2013, Viennot & Décamp 2013, Décamp & Viennot 2014). Further research is needed to support this claim. New insight in these research domains would be precious, in particular to inform rational decisions relating to the crucial question of how better to engage students in physics.

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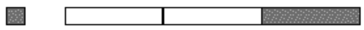
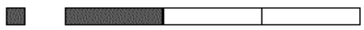
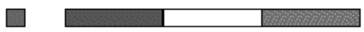
Appendix Colour phenomena: classical rules

Here the colours are associated with “thirds of the spectrum”

Separating the various radiations that constitute “white” light gives a “spectrum”. The spectrum of white light ranges from λ = 400 nm to λ = 700 nm. (λ: wavelength in empty space; 1 nm = 10^{-9} m)

Here the spectrum is divided diagrammatically into three equal parts.	
Coloured lights with a spectrum corresponding to a third of the preceding one are seen respectively as red in the long wavelengths	
green in the medium wavelengths	
blue in the short wavelengths	

Additive mixing*: Combining these three lights in various proportions produces a wide range of colours and, when the proportions are right, white.*
Adding two of these lights in correct proportion gives respectively a light seen as

- yellow if you add red light and green light	
- cyan, if you add blue light and green light	
- magenta, if you add red light and blue light	

Absorbing role of filters or pigments
A filter (or a pigment) absorbs a part of the spectrum of white light :

- a yellow filter absorbs blue light (a third) and diffusely reflects green and red lights.	
- a cyan filter absorbs red light (a third) and diffusely reflects blue and green lights.	
- a magenta filter absorbs green light (a third) and diffusely reflects blue and red lights.